Evidence of the Schwinger Mechanism in QCD

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Based on:

A. C. A, M. N. Ferreira and J. Papavassiliou, Phys. Rev. D105, no.1, 014030 (2022)

A.C.A., F. De Soto, M. N. Ferreira, J. Papavassiliou, F. Pinto-Gómez, C. D. Roberts, J.Rodríguez-Quintero, *Phys. Lett.B* 841 (2023) 137906

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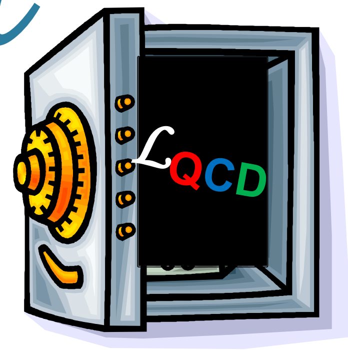
Outline of the talk

- Motivation - Emergence of a dynamical gluon mass
- Difficulties to generate a gluon mass → seagull cancellation
- Schwinger Mechanism in QCD and the presence of massless in the fundamental vertices
- Dynamical generation of the massless poles – Bethe Salpeter equation
- Displacement of the Ward identity – the smoking gun signal of the Schwinger Mechanism in QCD
- Conclusions

Dynamical generation of a gluon mass



- The gauge fields (gluons) are masless at the level **QCD** lagrangian

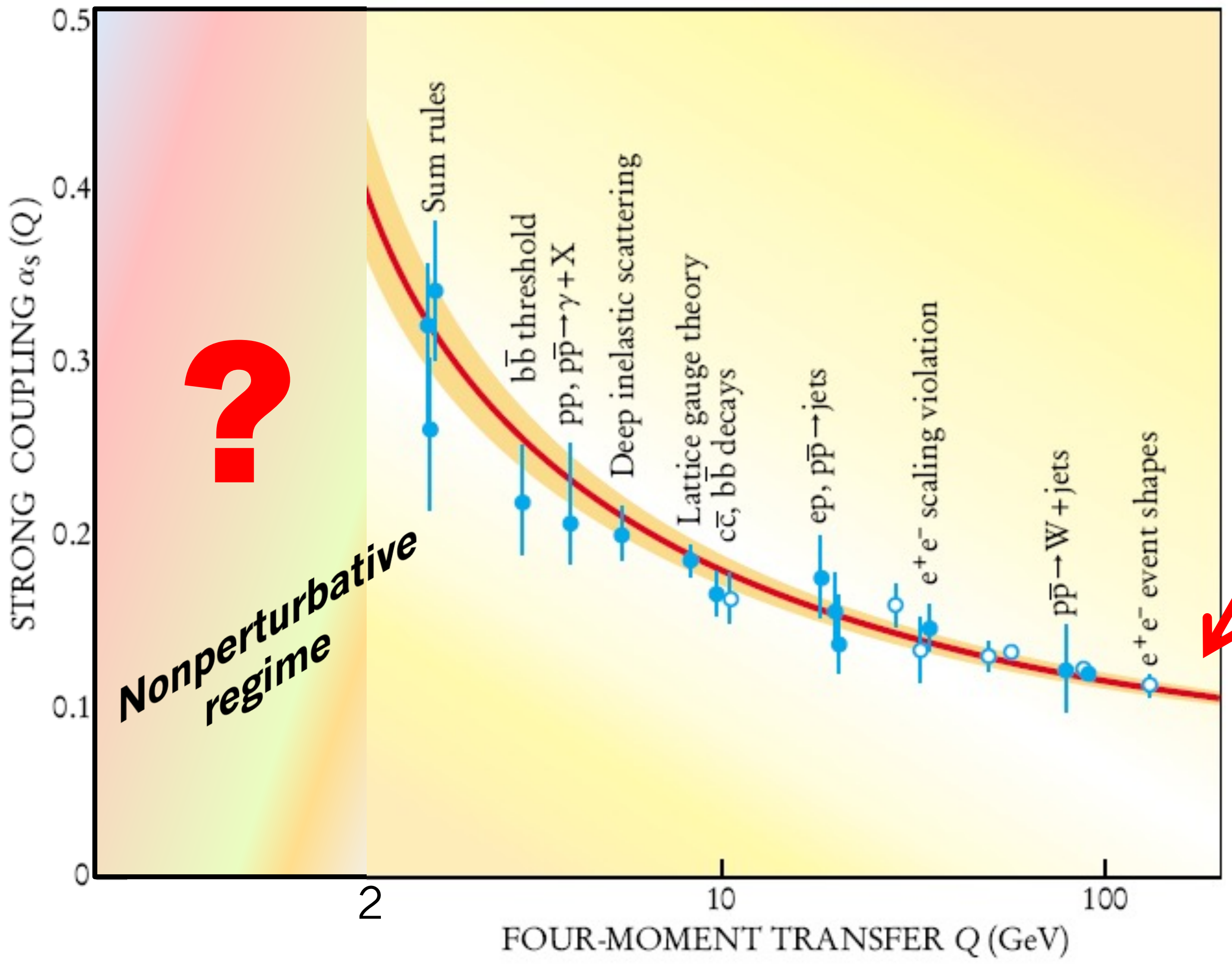
$$\mathcal{L}_{YM} = -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + \frac{1}{2\xi}(\partial^\mu A_\mu^a)^2 + \bar{c}^a(-\partial^\mu D_\mu^{ac})c^c$$

where the gluonic field strength tensor

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

- A mass term ($m^2A_\mu^2$) is forbidden by gauge invariance.
- The mechanism should not generate quadratic divergences → to renormalize them away you must add a mass term.

QCD coupling constant



The strongest force in the nature turns off at large momentum values

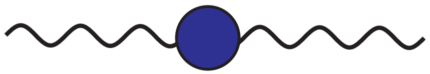
Asymptotic fredoom

Objects of interest:

Green's functions

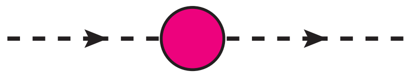
- Full propagators defined as vaccum expectation value of the fields

$$\langle \Omega | T\{A_\mu^a(x) A_\nu^b(y)\} | \Omega \rangle := -i\Delta_{\mu\nu}^{ab}(x-y)$$



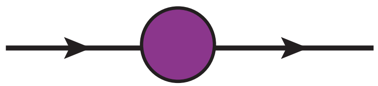
Gluon propagator

$$\langle \Omega | T\{c^a(x) \bar{c}^b(y)\} | \Omega \rangle := iD^{ab}(x-y)$$



Ghost propagator

$$\langle \Omega | T\{\psi(x) \overline{\psi}(y)\} | \Omega \rangle := iS(x-y)$$



Quark propagator

Off-shell QCD Green's functions

Green's functions:

Propagators and vertices

⇩

Although they are:

- Gauge-dependent
- Renormalization point (μ) and scheme-dependent

However

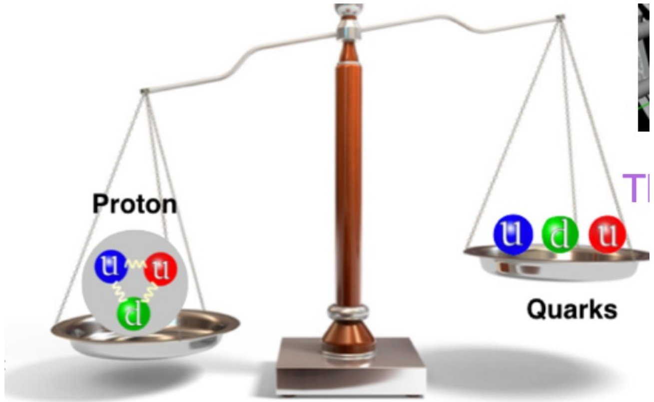
- They capture characteristic features of the underlying dynamics, both perturbative and non-perturbative.
- When appropriately combined they give rise to physical observables.

Crucial pieces for completing the QCD puzzle

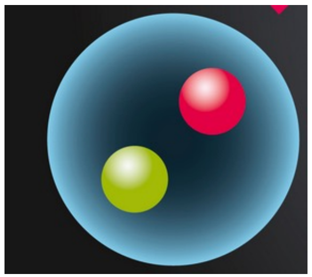
The nonperturbative QCD problems

◎ The Green's functions are crucial for exploring the outstanding nonperturbative problems of QCD:

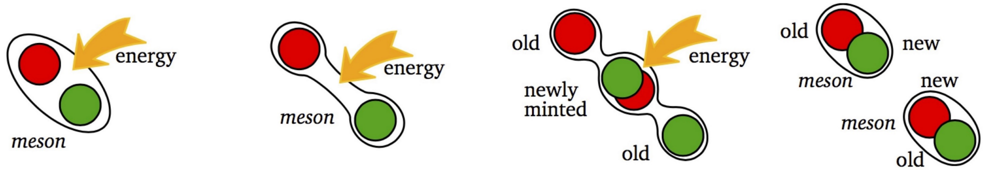
Emergence of mass scale (quark and gluon masses)



Bound states formation

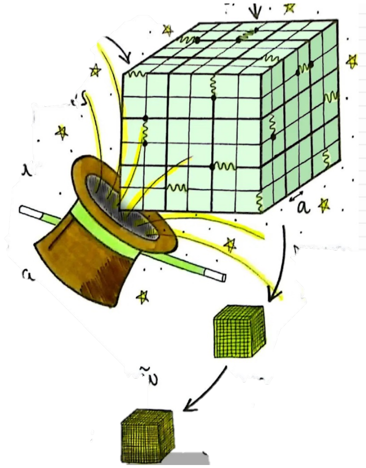


Confinement

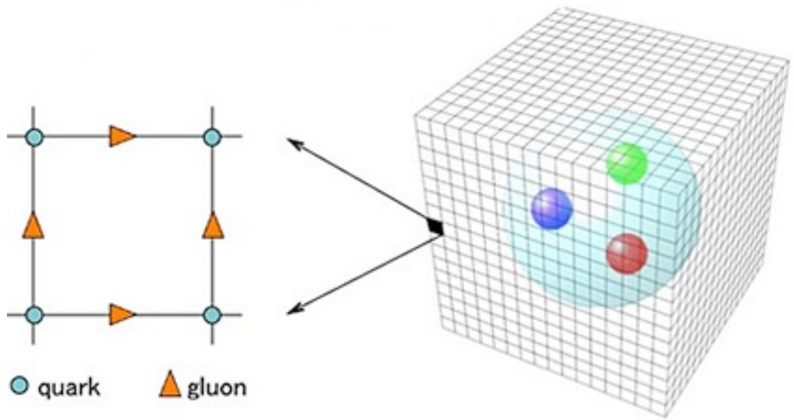


Non-pertubative tools

- Non-perturbative physics requires special tools.
- For QCD we have (first principles):
- Lattice simulations



Source: Blog Coleção de Partículas - IFSC



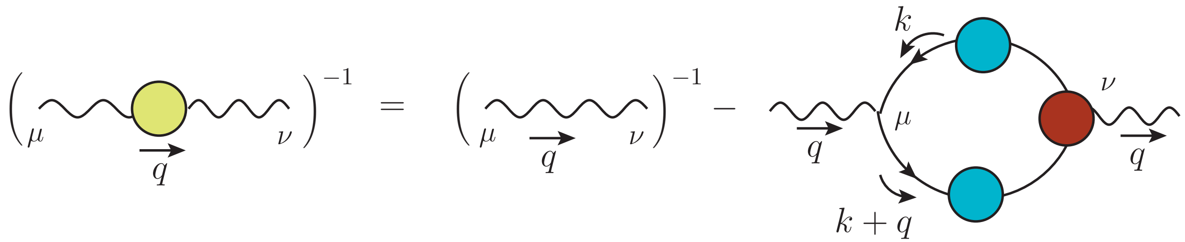
- Space-time is discretized;
- The precision depends on the lattice spacing parameter and volume.

Schwinger-Dyson equations

- Insightful computational framework

- Equations of motion for off-shell Green's functions.

- Derived formally from the generating functional.



- Infinite system of coupled non-linear integral equations

- Inherently non-perturbative, but at the same time captures the perturbative behavior → It accommodates the full range of physical momenta.

Difficulties with SDEs

- The need for truncations is evident

  ✓ No obvious expansion parameter, so, no formal way of estimating the size of the omitted terms. However, it seems that the "projection" of higher Green's functions on the lower ones is "small".

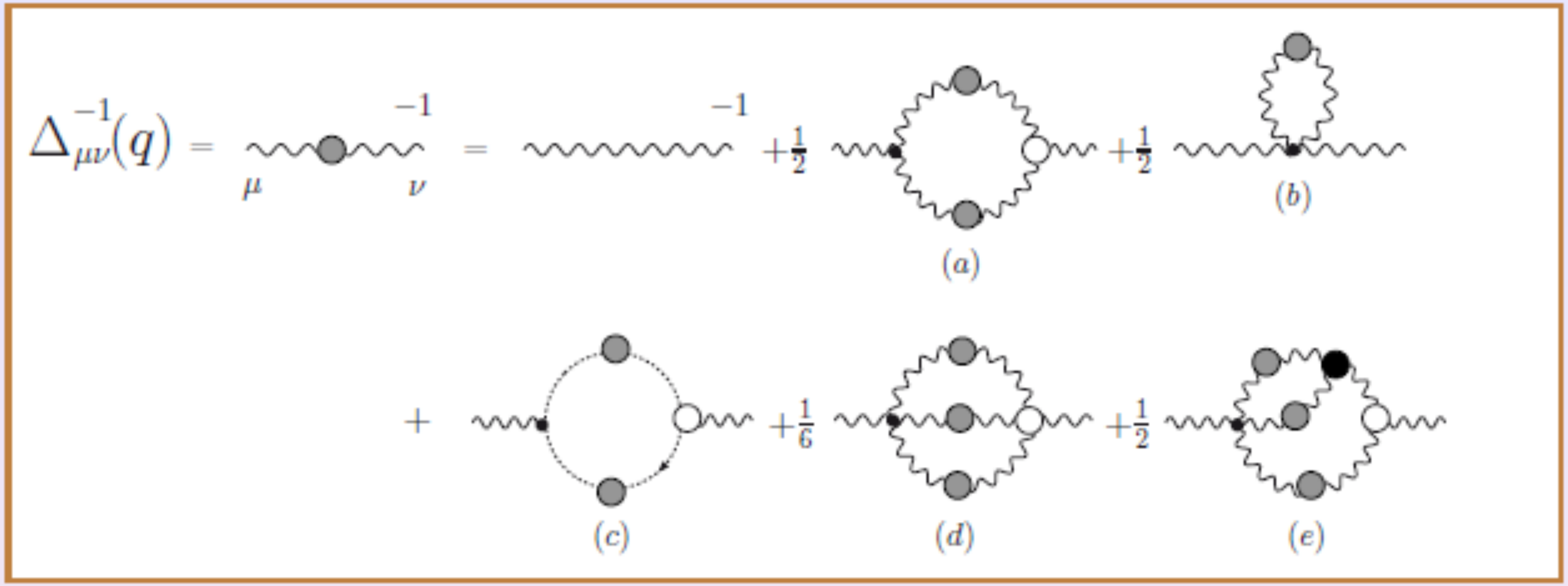
  ✓ Casual truncation interferes with the symmetries encoded in the form of the SDEs

$$q^{\mu}\Pi_{\mu\nu}(q) = 0 \quad \Longrightarrow \quad \Pi_{\mu\nu}(q) = \left[g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right]\Pi(q^2)$$

$\Pi_{\mu\nu}(q)$ *is the gluon self-energy*
It is transverse

- Self-consistent **truncation scheme** must be used.

The complete SDE for the gluon propagator



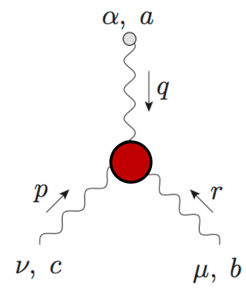
◎ Retaining only (a) and (b) is not correct even at one loop

$$q^{\mu}\Pi_{\mu\nu}(q)|_{(a)+(b)} \neq 0$$

◎ Adding (c) is not sufficient for a full analysis → beyond one loop

$$q^{\mu}\Pi_{\mu\nu}(q)|_{(a)+(b)+(c)} \neq 0$$

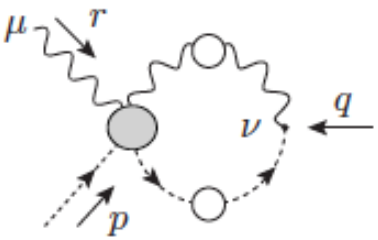
Slavnov Taylor identities



- The main problem is that fully dressed vertices satisfy STIs instead of WI.

$$q^\alpha \Gamma_{\alpha\mu\nu}(q,r,p) = F(q)\left[\Delta^{-1}(p)P_\nu^\alpha(p)H_{\mu\alpha}(r,p) - \Delta^{-1}(r)P_\mu^\alpha(r)H_{\nu\alpha}(p,r)\right]$$

$$H_{\nu\mu}(q,p,r) = g_{\mu\nu} +$$



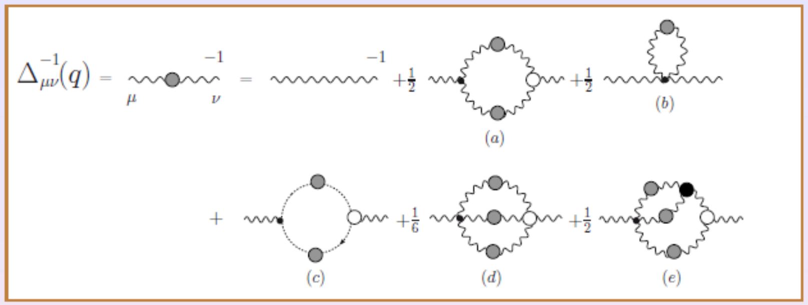
$$D(q^2) = \frac{F(q^2)}{q^2}$$

$$\Delta^{-1}(q^2) = q^2 J(q^2)$$

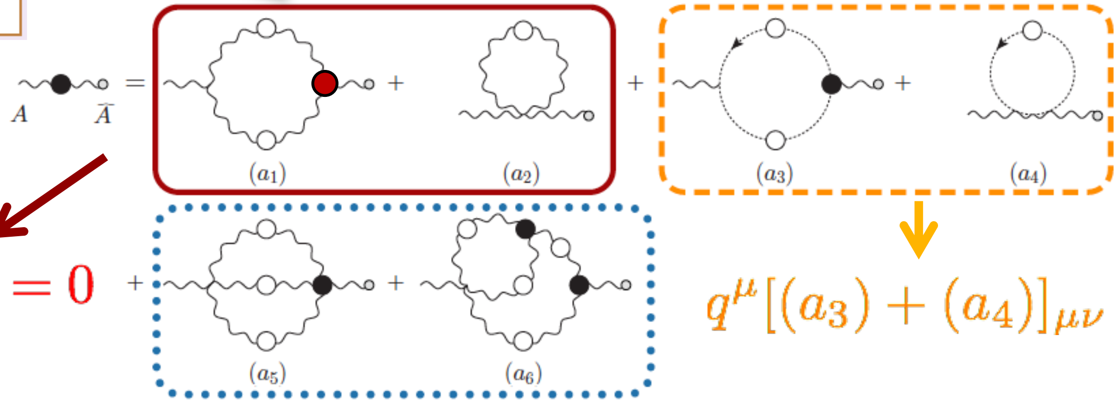
$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

- All diagrams must conspire to maintain intact crucial properties of the theory.
- If one truncates “naively”, i.e., just by dropping diagrams without a guiding principle → one will violate the fundamental transversality property.
- *To avoid that → use SDE in the Pinch Technique - Background field method (PT-BFM) formalism*
- Split the gauge field $A_\mu^a \to B_\mu^a + Q_\mu^a$

Pinch Technique - Background Field Method



$$\Delta(q) = \widetilde{\Delta}(q)[1 + G(q)]$$



$$q^{\mu}[(a_1) + (a_2)]_{\mu\nu} = 0$$

$$q^{\mu}[(a_3) + (a_4)]_{\mu\nu} = 0$$

$$q^{\mu}[(a_5) + (a_6)]_{\mu\nu} = 0$$

- **Transversality** is enforced separately for gluon and ghost loops, and order by order in the "dressed-loop" expansion!

$$q^{\mu}\widetilde{\Gamma}_{\mu\alpha\beta}(q,r,p) = i\Delta^{-1}_{\alpha\beta}(r) - i\Delta^{-1}_{\alpha\beta}(p) \quad \Rightarrow \quad q^{\mu}[(a_1) + (a_2)]_{\mu\nu} = 0$$

$$q^{\mu}\widetilde{\Gamma}_{\mu}(q,r,-p) = D^{-1}(p) - D^{-1}(r) \quad \Rightarrow \quad q^{\mu}[(a_3) + (a_4)]_{\mu\nu} = 0$$

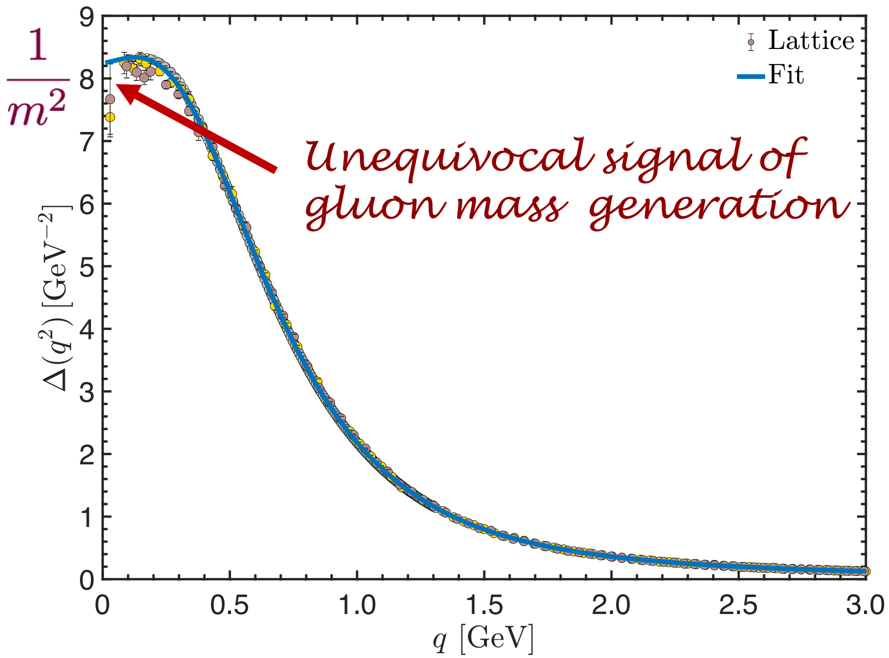
$$q^{\mu}\widetilde{\Gamma}^{mnrs}_{\mu\alpha\beta\gamma} = f^{mse}f^{ern}\Gamma_{\alpha\beta\gamma} + f^{mne}f^{esr}\Gamma_{\beta\gamma\alpha} + f^{mre}f^{ens}\Gamma_{\gamma\alpha\beta} \quad \Rightarrow \quad q^{\mu}[(a_5) + (a_6)]_{\mu\nu} = 0$$

A.C. A. and J.Papavassiliou, JHEP 0612, 012 (2006)
D. Binosi and J. Papavassiliou, Phys.Rev. D 77, 061702 (2008); JHEP 0811:063,2008.

Emergence of a dynamical gluon mass

- Gluon self-interactions generate a dynamical mass.

- Lattice QCD: The gluon propagator saturates in the deep infrared.



I.L.Bogolubsky, et al , PoS **LAT2007**, 290 (2007)
A.Cucchieri and T.Mendes, PoS **LAT2007**, 297 (2007)
O.Oliveira and P.J.Silva, PoS **QCD-TNT09**, 033 (2009)

A. C. A., D. Binosi and J. Papavassiliou, Phys.Rev. D78 (2008) 025010

The gluon propagator (in Landau gauge)

$$\Delta^{\mu\nu}(q) = \left[g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right]\Delta(q^2)$$

- IR saturation is explained through *gluon mass generation*

J. M. Cornwall, Phys. Rev. D26, 1453 (1982)

$$\Delta(q^2) \sim \frac{1}{q^2 + m^2 + q^2 c \ln\left(\frac{q^2+m^2}{\Lambda^2}\right) + \cdots}$$

$$\Delta(0)^{-1} = m^2$$

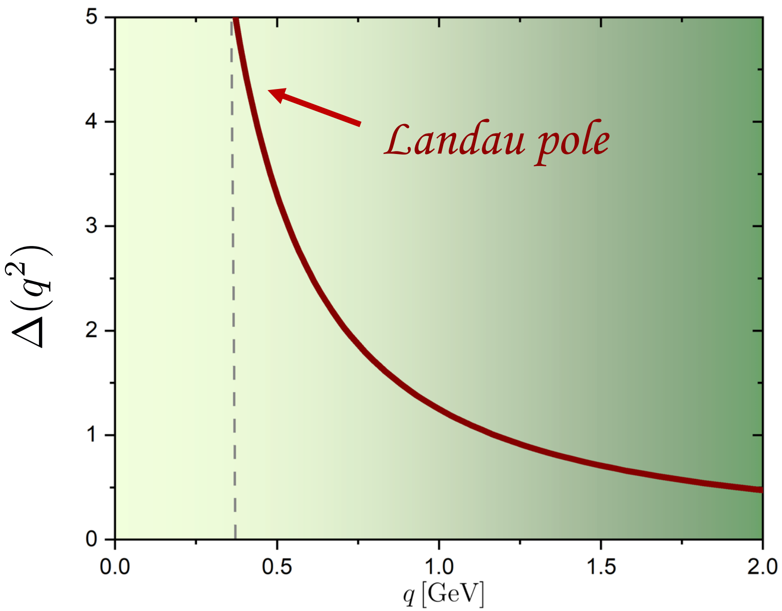
- A deep mechanism is at work: *dynamics and symmetry are tightly interlocked*

- Properly regularized perturbation theory cannot generate mass at any finite order

- Perturbative results are plagued with unphysical divergences (Landau pole).

- For example: Gluon propagator

$$\Delta(q^2) \sim \frac{1}{q^2\left[1 + c\ln\left(\frac{q^2}{\Lambda^2}\right) + \cdots\right]}$$



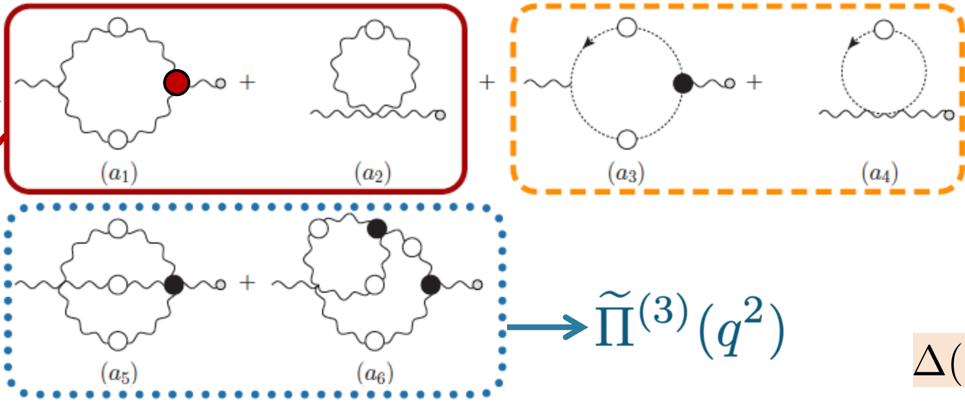
However, the theory cures its divergences nonperturbatively

Question 1: How can one generate a gluon mass (saturation of the gluon propagator a zero momentum) without breaking the gauge symmetry?

It is not so simple because the QCD displays a similar cancellation that protects the photon to be massive in QED.

Seagull cancellation

$$\widetilde{\Delta}^{-1}(q^2) = \widetilde{\Delta}_0^{-1}(q^2) +$$



$\widetilde{\Pi}^{(1)}(q^2)$ $\widetilde{\Pi}^{(2)}(q^2)$ $\widetilde{\Pi}^{(3)}(q^2)$

$$\Delta(q) = \widetilde{\Delta}(q)[1 + G(q)]$$

$$\widetilde{\Delta}^{-1}(q^2) = q^2 + i\left[\widetilde{\Pi}^{(1)}(q^2) + \widetilde{\Pi}^{(2)}(q^2) + \widetilde{\Pi}^{(3)}(q^2)\right]$$

PT- BFM Ward-Takahashi identities + **Seagull cancellation** = $\widetilde{\Delta}^{-1}(0) = 0$

$$q^\mu \widetilde{\Gamma}_{\mu\alpha\beta}(q,r,p) = i\Delta^{-1}_{\alpha\beta}(r) - i\Delta^{-1}_{\alpha\beta}(p)$$

$$q^\mu \widetilde{\Gamma}_{\mu}(q,r,-p) = D^{-1}(p) - D^{-1}(r)$$

⋮

ACA and J. Papavassiliou Phys. Rev. D 81, 034003 (2010)

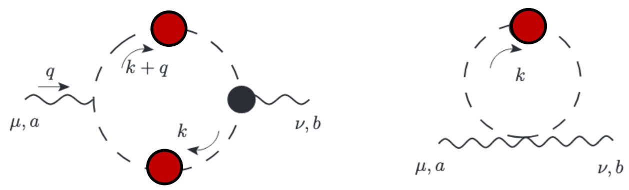
Seagull cancellation

(valid in dimensional regularization)

$$\int_k k^2 \frac{\partial f(k^2)}{\partial k^2} + \frac{d}{2}\int_k f(k^2) = 0$$

Seagull identity in the Scalar QED

$$\Pi^{(1)}_{\mu\nu}(q) =$$



(d_1) (d_2)

the full vertex satisfies the WTI

$$q^\mu \Gamma_\mu(q, r, -p) = \mathcal{D}^{-1}(p) - \mathcal{D}^{-1}(r)$$

and the WIs

$$\Gamma_\mu(0, r, -r) = \frac{\partial}{\partial r^\mu}\mathcal{D}^{-1}(r)$$

$$\Pi^{(1)}_{\mu\nu}(q) = (d_1)_{\mu\nu} + (d_2)_{\mu\nu},$$

$$\Pi^{(1)}_{\mu\nu}(q) = \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Pi^{(1)}(q^2).$$

$$(d_1)_{\mu\nu} = e^2 \int_k (2k+q)_\mu \mathcal{D}(k)\mathcal{D}(k+q)\Gamma_\nu(-q, k+q, -k),$$

$$(d_2)_{\mu\nu} = -2e^2 g_{\mu\nu} \int_k \mathcal{D}(k^2),$$

- Taking the limit q → 0, we have that $g^{\mu\nu}$ component

$$d_1 = \frac{2e^2}{d}\int_k k_\mu \mathcal{D}^2(k^2)\Gamma^\mu(0, k, -k),$$

$$d_2 = -2e^2 \int_k \mathcal{D}(k^2).$$

Use the WIs

$$d_1 = -\frac{4e^2}{d}\int_k k^2 \frac{\partial \mathcal{D}(k^2)}{\partial k^2},$$

- Thus, we find

$$\Pi^{(1)}(0) = -\frac{4e^2}{d}\underbrace{\left[\int_k k^2 \frac{\partial \mathcal{D}(k^2)}{\partial k^2} + \frac{d}{2}\int_k \mathcal{D}(k^2)\right]}_{\text{seagull}}.$$

$$\Pi^{(1)}(0) = 0$$

ACA, D. Binosi, C. T. Figueiredo. and J. Papavassiliou, Phys. Rev. D94, no. 4, 045002 (2016).

Question 2: How can one evade the seagull cancellation and get a gluon mass?

Answer: Introduce massless poles to trigger the Schwinger Mechanism

J. S. Schwinger, Phys. Rev.125, 397 (1962);
Phys.Rev.128, 2425 (1962).

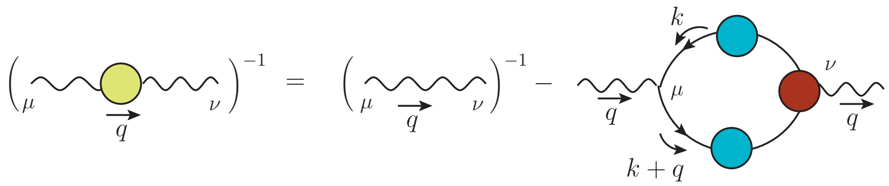
Gauge invariance and mass

A gauge boson may acquire a mass, even if the gauge symmetry forbids a mass term at the level of the fundamental Lagrangian, provided that its vacuum polarization function develops a pole at zero momentum transfer.

Schwinger Mechanism

J. S. Schwinger, Phys. Rev.125, 397 (1962);
Phys.Rev.128, 2425 (1962).

- Schwinger-Dyson Equation for the gauge boson



$$\Delta^{-1}(q^2) = q^2[1 + \mathbf{\Pi}(q^2)]$$

- If the vaccum polarization has a pole in $q^2 = 0$ with positive residue m^2, i.e.

$$\Pi(q^2) = \frac{m^2}{q^2}$$

Massless poles

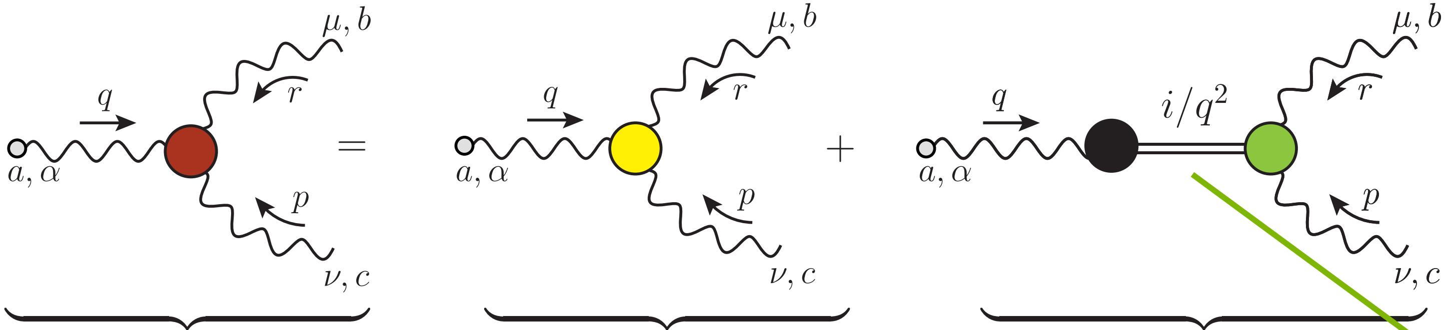
- Then

$$\Delta^{-1}(q^2) = q^2 + m^2 \quad \Rightarrow \quad \Delta^{-1}(0) = m^2$$

Dynamical mass generation requires the emergence of massless poles in the vaccum polarization → coming from the vertices (nonpertubative origin)

Vertices with massless poles in QCD

- To evade the seagull cancellation, let us introduce poles of the type $1/q^2$ in the full three gluon vertex



$$\widetilde{\mathbb{\Gamma}}_{\alpha\mu\nu}(q,r,p) = \widetilde{\Gamma}_{\alpha\mu\nu}(q,r,p) + \widetilde{V}_{\alpha\mu\nu}(q,r,p)$$

Massless poles

$$\begin{aligned}\widetilde{V}_{\alpha\mu\nu}(q,r,p) &= \frac{q_\alpha}{q^2}\widetilde{C}_{\mu\nu}(q,r,p) \\ &= \frac{q_\alpha}{q^2}\left[\widetilde{C}_1 g_{\mu\nu} + \widetilde{C}_2 r_\mu r_\nu + \widetilde{C}_3 p_\nu p_\mu + \widetilde{C}_4 r_\mu p_\nu + \widetilde{C}_5 p_\mu r_\nu\right]\end{aligned}$$

$$P^{\alpha}_{\alpha'}(q)P^{\mu}_{\mu'}(r)P^{\nu}_{\nu'}(p)\widetilde{V}_{\alpha\mu\nu}(q,r,p) = 0$$

$$P_{\mu\nu}(q) = \left[g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right]$$

Longitudinally coupled
Drops out when embedded in a S-matrix element and also in transversely projected Green's functions

But what happens with the Ward Takahashi identity that this vertex satisfies?

Ward identity in the presence of poles

$$\widetilde{\mathrm{I\Gamma}}_{\alpha\mu\nu}(q,r,p) = \widetilde{\Gamma}_{\alpha\mu\nu}(q,r,p) + \frac{q_\alpha}{q^2}\widetilde{C}_{\mu\nu}(q,r,p)$$

$$\widetilde{V}_{\alpha\mu\nu}(q,r,p) = \frac{q_\alpha}{q^2}\widetilde{C}_{\mu\nu}(q,r,p)$$

$$\widetilde{C}_{\mu\nu}(q,r,p) = \widetilde{C}_1 g_{\mu\nu} + \cdots$$

$$q^\alpha \widetilde{\mathrm{I\Gamma}}_{\alpha\mu\nu}(q,r,p) = i\Delta^{-1}_{\mu\nu}(r) - i\Delta^{-1}_{\mu\nu}(p)$$

Same WTI identity !

$$q^\alpha \widetilde{\Gamma}_{\alpha\mu\nu}(q,r,p) + \widetilde{C}_{\mu\nu}(q,r,p) = i\Delta^{-1}_{\mu\nu}(r) - i\Delta^{-1}_{\mu\nu}(p)$$

$q \to 0$

$p \to -r$

Taylor expansion $\mathcal{O}(q^2)$

$$q^\alpha \widetilde{\Gamma}_{\alpha\mu\nu}(0,r,-r) + \widetilde{C}_{\mu\nu}(0,r,-r) + q^\alpha \left\{ \frac{\partial}{\partial q^\alpha}\widetilde{C}_{\mu\nu}(q,r,p) \right\}_{q=0} = -iq^\alpha \frac{\partial \Delta^{-1}_{\mu\nu}(r)}{\partial r^\alpha}$$

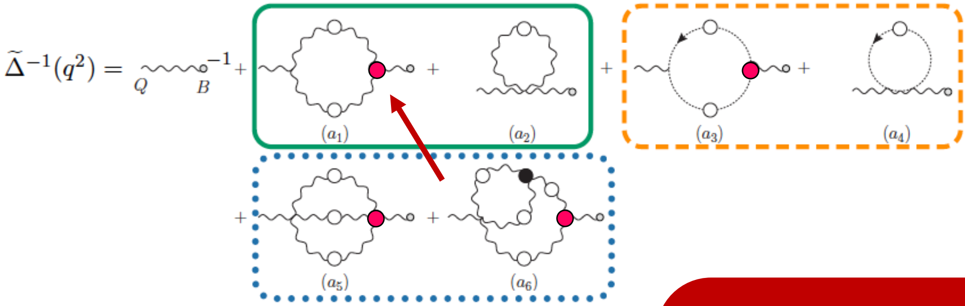
Using that $\widetilde{C}_{\mu\nu}(0,r,-r) = 0$, we obtain (keep only terms linear in q)

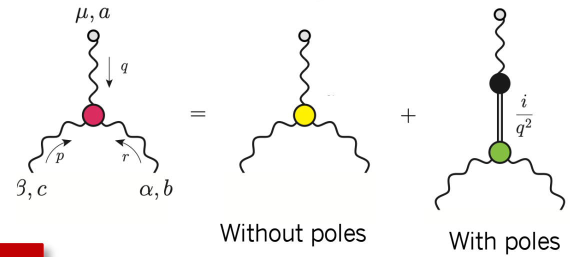
$$\widetilde{\Gamma}_{\alpha\mu\nu}(0,r,-r) = -i\frac{\partial \Delta^{-1}_{\mu\nu}(r)}{\partial r^\alpha} - \underbrace{\left\{ \frac{\partial}{\partial q^\alpha}\widetilde{C}_{\mu\nu}(q,r,p) \right\}_{q=0}}_{\mathbb{C}(r^2)}$$

Ward identity suffers a displacement

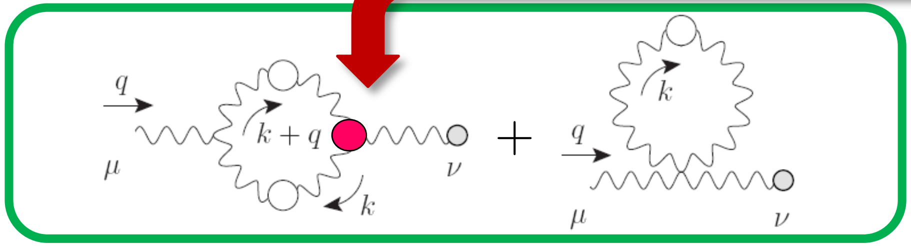
$$\mathbb{C}(r^2) := \left[\frac{\partial C_1(q,r,p)}{\partial p^2}\right]_{q=0}$$

Evading the seagull identity

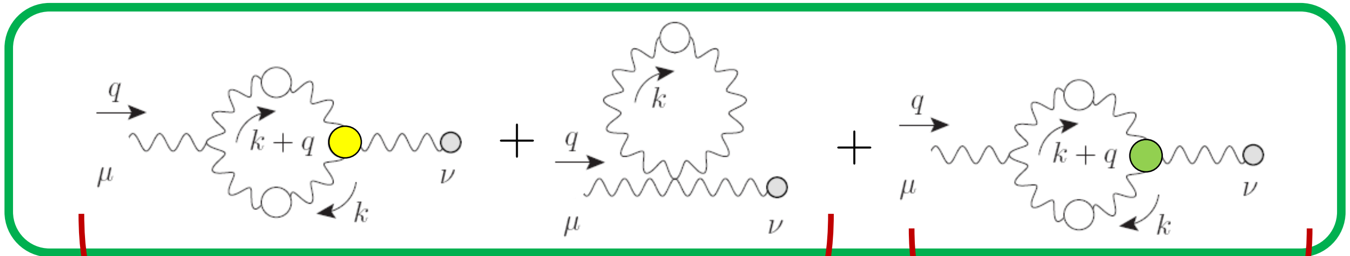




$\widetilde{\Delta}^{-1}(0) = \lim_{q\to 0}$



$= \lim_{q\to 0}$



Triggers seagull identity exactly as before

Vanishes identically

pole contribution

$\propto \mathbb{C}(k^2)$

$$\Delta^{-1}(0) \sim \int_k k^2 \Delta^2(k) \mathbb{C}(r^2)$$

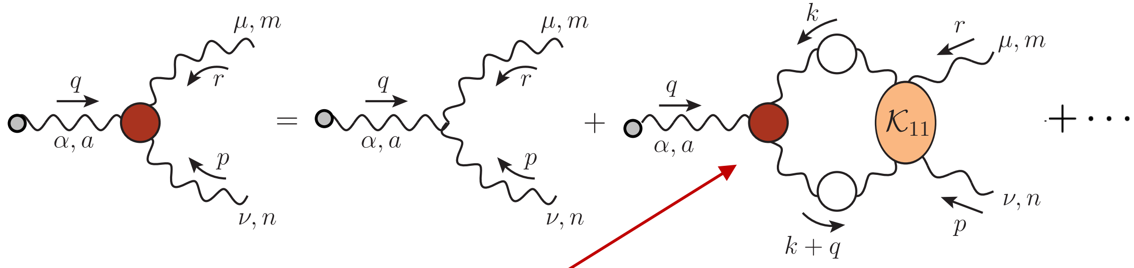
Saturation!
Gluon mass Generated related to the massless poles

ACA, D.Binosi, C.T.Figueiredo and J.Papavassiliou, Phys. Rev. D 94, no. 4, 045002 (2016)

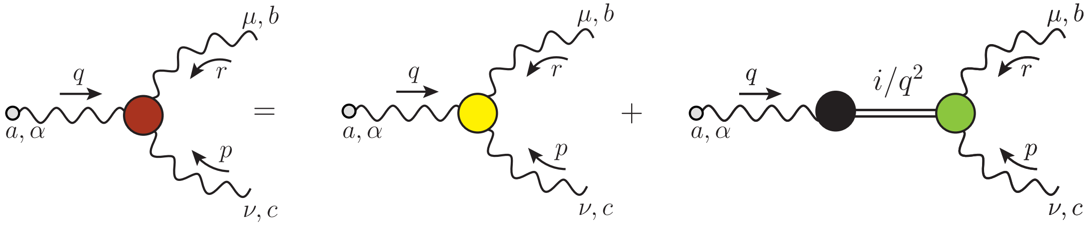
Question 3: How the QCD dynamics generates the massless poles which appear in the fundamental vertices?

Dynamical equation for the massless pole

Equation for
the full vertex
$\mathrm{I\!\Gamma}_{\mu}(q,r,p)$



Substitute:



$$\mathrm{I\!\widetilde{\Gamma}}_{\alpha\mu\nu}(q,r,p) = \widetilde{\Gamma}_{\alpha\mu\nu}(q,r,p) + \widetilde{V}_{\alpha\mu\nu}(q,r,p)$$

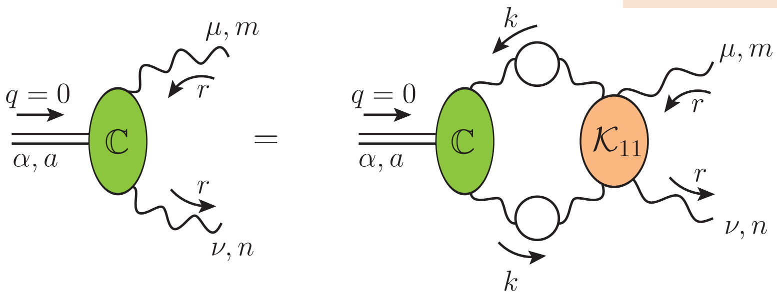
$$\widetilde{V}_{\alpha\mu\nu}(q,r,p) = \frac{q_\alpha}{q^2}\Big[\underbrace{\widetilde{C}_1(q,r,p)}_{\text{residue}}\, g_{\mu\nu} + \cdots\Big]$$

Take the limit

$$q \to 0$$

$$\lim_{q\to 0} \widetilde{C}_1(q,r,p) = 2(q\cdot r)\underbrace{\left[\frac{\partial \widetilde{C}_1(q,r,p)}{\partial p^2}\right]_{q=0}}_{\mathbb{C}(r^2)} + \mathcal{O}(q^2)$$

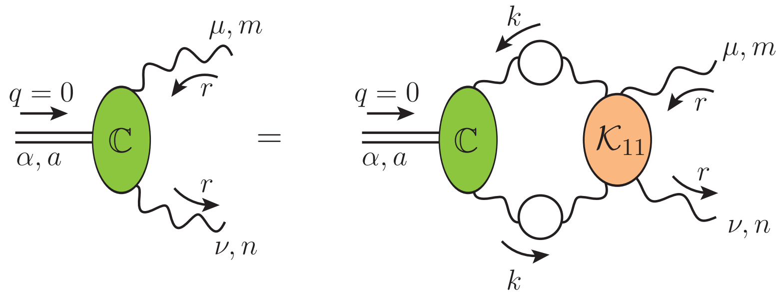
It is the
Bethe-Salpeter
Equation for the
massless pole!



Describes the formation of the dynamical formation of massless pole

$$\mathbb{C}(r^2) = \alpha_s \int_k \mathbb{C}(k^2)\Delta^2(k)\mathcal{K}_{11}(k,r)$$

Dynamical equation for the massless pole



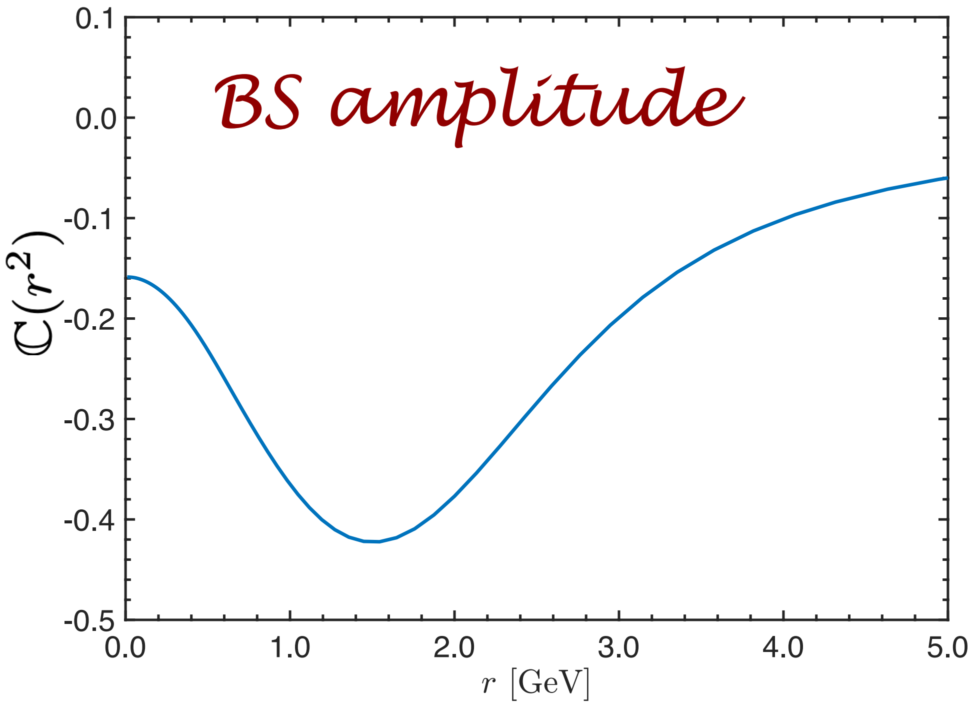
$$\mathbb{C}(r^2) = \alpha_s \int_k \mathbb{C}(k^2)\Delta^2(k)\mathcal{K}_{11}(k,r)$$

- *Eigenvalue problem*

- Solution when $\alpha_s \approx 0.3$ @ $\mu = 4.3\,\text{GeV}$

- Directly connected with the gluon mass

$$m^2 = \Delta^{-1}(0) \sim \int_k k^2\Delta^2(k)\mathbb{C}(r^2)$$



A.C.A, D.Binosi, C.T.Figueiredo and J.Papavassiliou, Eur. Phys. J. C78 (2018) no.3, 181

- Gluon propagator acquires a mass (self-stabilizing effect).

The theory solves its infrared problems

Question 4: Is there a way to confirm that the action of the Schwinger Mechanism in QCD using the lattice results?

The signal: Displacement of the Ward identity

Schwinger mechanism off

Ward Takahashi identity

$$q^\mu \underbrace{\Gamma_\mu(q,r,-p)}_{\text{pole-free}} = \mathcal{D}^{-1}(p) - \mathcal{D}^{-1}(r)$$

$q \to 0$, $p \to r$: Taylor expansion

Ward identity

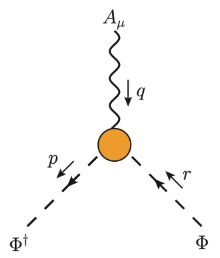
$$\Gamma_\mu(0,r,-r) = \frac{\partial \mathcal{D}^{-1}(r)}{\partial r^\mu}$$

Tensorial decomposition (Soft photon limit)

$$\Gamma_\mu(0,r,-r) = L_{sg}(r^2) r_\mu$$

$$\boxed{L_{sg}(r^2) = 2\frac{\partial \mathcal{D}^{-1}(r)}{\partial r^2}}$$

Scalar QED



Schwinger mechanism on

$$\mathbb{\Gamma}_\mu(q,r,-p) = \underbrace{\Gamma_\mu(q,r,-p)}_{\text{pole-free}} + \frac{q_\mu}{q^2}\mathfrak{C}(q,r,-p)$$

The Ward Takahashi identity **does not change**

$$q^\mu \mathbb{\Gamma}_\mu(q,r,-p) = q^\mu \Gamma_\mu(q,r,-p) + \mathfrak{C}(q,r,-p)$$
$$= \mathcal{D}^{-1}(p) - \mathcal{D}^{-1}(r)$$

$q \to 0$, $p \to r$: Taylor expansion

Ward identity

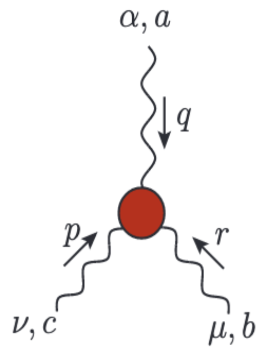
$$\Gamma_\mu(0,r,-r) = \frac{\partial \mathcal{D}^{-1}(r)}{\partial r^\mu} - 2r_\mu \underbrace{\left[\frac{\partial \mathfrak{C}(q,r-p)}{\partial p^2}\right]_{q=0}}_{\mathbb{C}(r^2)}$$

$$\boxed{L_{sg}(r^2) = 2\frac{\partial \mathcal{D}^{-1}(r)}{\partial r^2} - \underbrace{2\mathbb{C}(r^2)}_{\text{displacement}}}$$

Displacement of the WI of the three-gluon vertex

- In the case of the full vertex three gluon vertex, we obtain

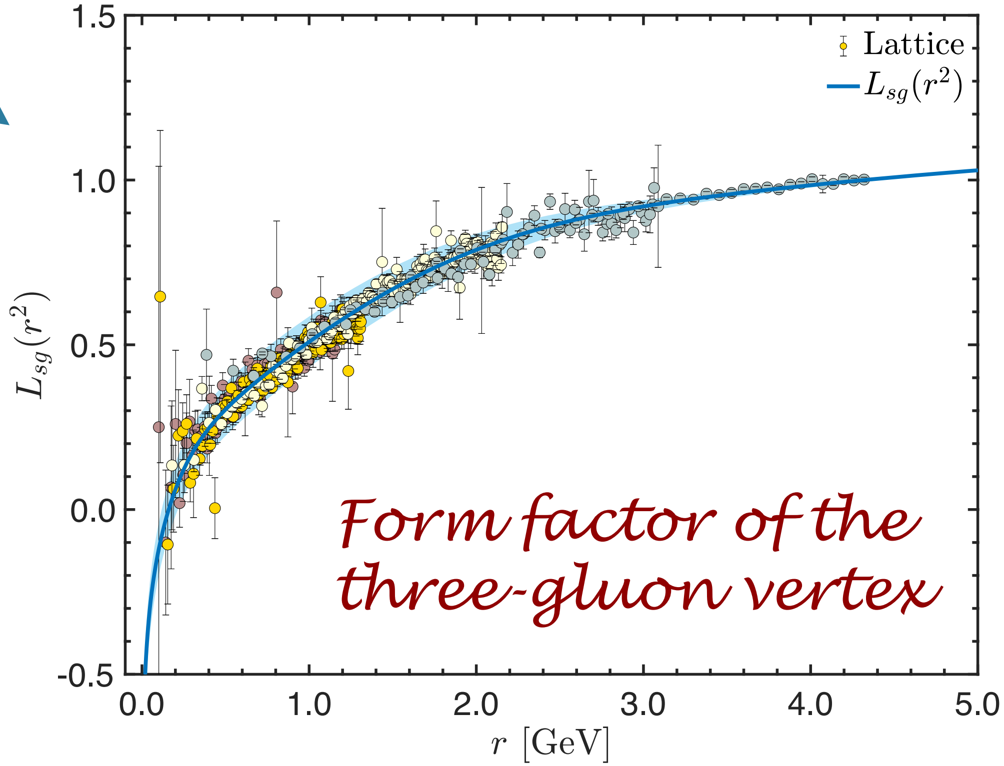
$$\underbrace{\mathbb{C}(r^2)}_{\text{displacement}} = L_{sg}(r^2) - F(0)\left\{\frac{\mathcal{W}(r^2)}{r^2}\Delta^{-1}(r^2) + \left[\frac{d\Delta^{-1}(r^2)}{dr^2}\right]\right\},$$



A.C.A., D. Binosi, C.T. Figueiredo and J.Papavassiliou, Phys. Rev. D 94, no.4, 045002 (2016);
A.C.A., M.N. Ferreira, and J.Papavassiliou, Phys. Rev. D 105, no.1, 014030 (2022);
A.C.A., F.De Soto, M. N. Ferreira, J. Papavassiliou, F. Pinto-Gómez, C.D. Roberts, J. Rodríguez-Quintero, [arXiv:2211.12594 [hep-ph]].

Displacement of the WI of the three-gluon vertex

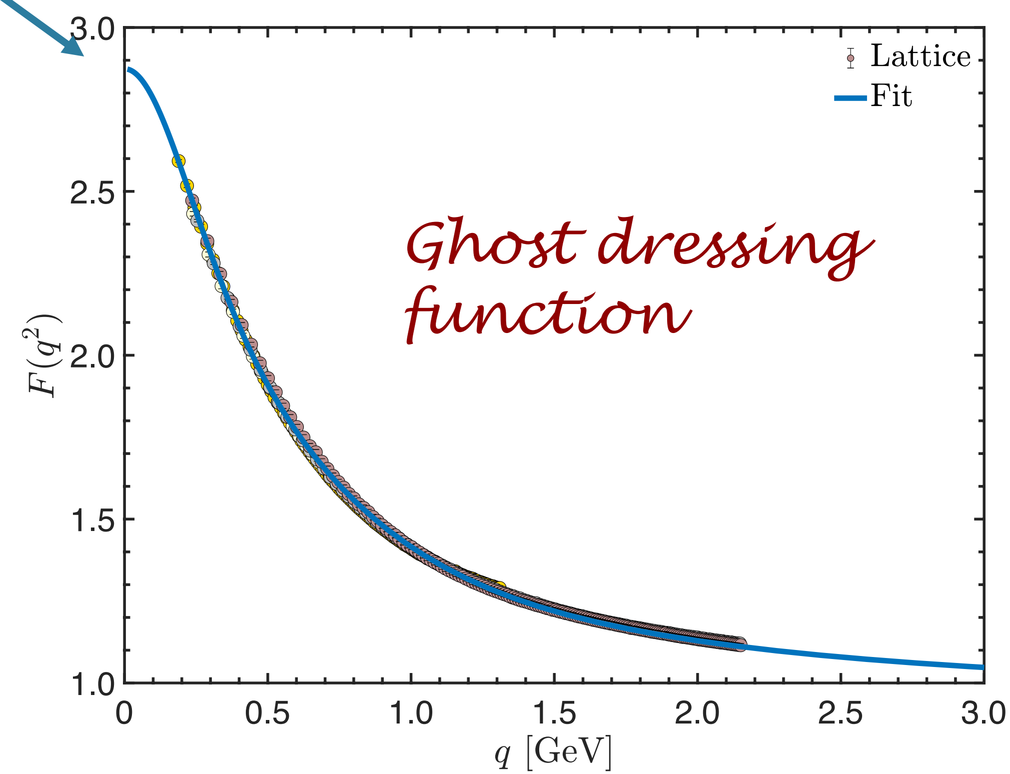
$$\underbrace{\mathbb{C}(r^2)}_{\text{displacement}} = \boxed{L_{sg}(r^2)} - F(0)\left\{\frac{\mathcal{W}(r^2)}{r^2}\Delta^{-1}(r^2) + \left[\frac{d\Delta^{-1}(r^2)}{dr^2}\right]\right\},$$



A.C. A., F. De Soto, M.N.Ferreira, J.Papavassiliou, J.Rodríguez-Quintero, Phys. Lett. B818 (2021) 136352.

Displacement of the WI of the three-gluon vertex

$$\underbrace{\mathbb{C}(r^2)}_{\textit{displacement}} = L_{sg}(r^2) - \boxed{F(0)}\left\{\frac{\mathcal{W}(r^2)}{r^2}\Delta^{-1}(r^2) + \left[\frac{d\Delta^{-1}(r^2)}{dr^2}\right]\right\}\,,$$



$$D(q^2) = \frac{F(q^2)}{q^2}$$

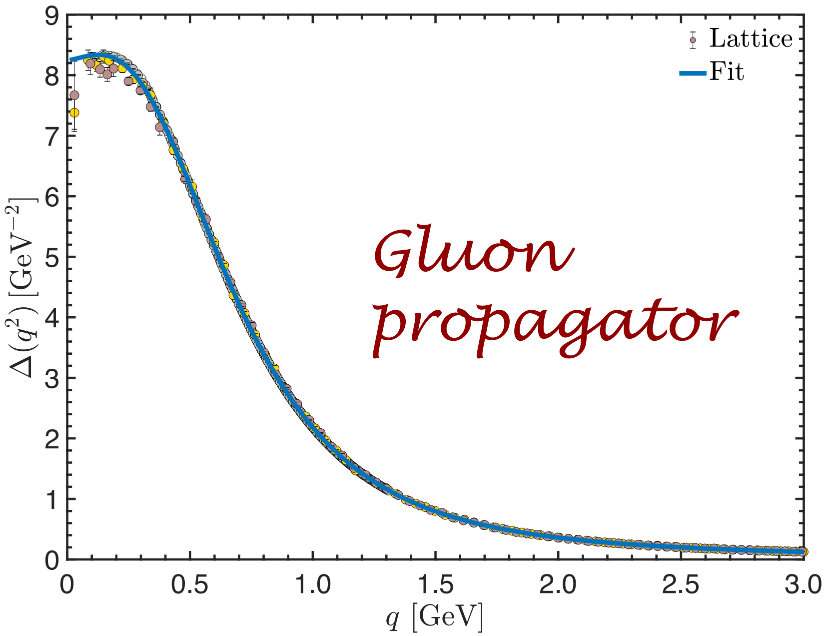
Ghost propagator

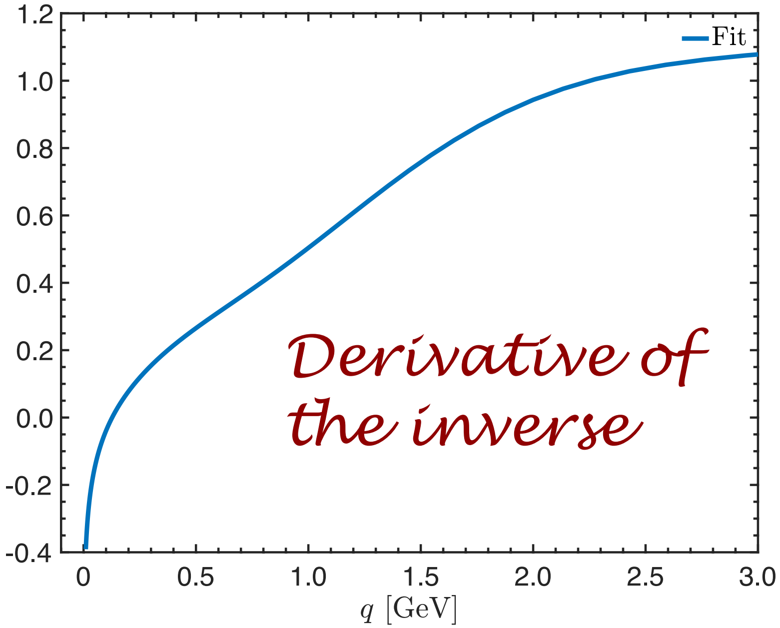
I.L.Bogolubsky, et al, PoS **LAT2007**, 290 (2007)
A.Cucchieri and T.Mendes, PoS **LAT2007**, 297 (2007)
O.Oliveira and P.J.Silva, PoS **QCD-TNT09**, 033 (2009)

A.C.A., C.O. Ambrosio, F. De Soto, M.N. Ferreira, B.M. Oliveira, J.Papavassiliou and J. Rodriguez-Quintero, Phys. Rev. D 104 no.5, 054028, (2021)

Displacement of the WI of the three-gluon vertex

$$\underbrace{\mathbb{C}(r^2)}_{\text{displacement}} = L_{sg}(r^2) - F(0)\left\{\frac{\mathcal{W}(r^2)}{r^2}\boxed{\Delta^{-1}(r^2)} + \boxed{\left[\frac{d\Delta^{-1}(r^2)}{dr^2}\right]}\right\},$$





I.L.Bogolubsky, et al , PoS **LAT2007**, 290 (2007)
A.Cucchieri and T.Mendes, PoS **LAT2007**, 297 (2007)
O.Oliveira and P.J.Silva, PoS **QCD-TNT09**, 033 (2009)

A.C.A., C.O. Ambrosio, F. De Soto, M.N. Ferreira, B.M. Oliveira, J.Papavassiliou and J. Rodriguez-Quintero, Phys. Rev. D 104 no.5, 054028, (2021)

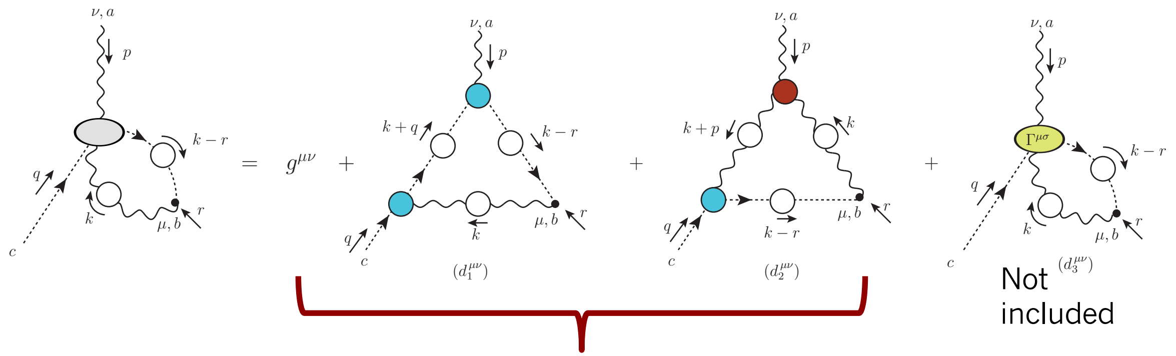
Displacement of the WI of the three-gluon vertex

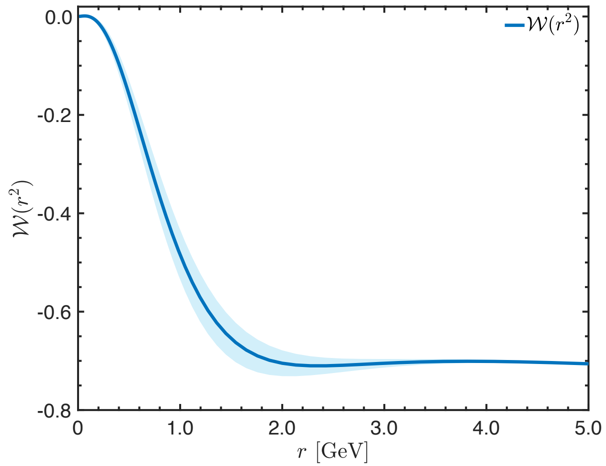
$$\underbrace{\mathbb{C}(r^2)}_{\text{displacement}} = L_{sg}(r^2) - F(0)\left\{\frac{\boxed{\mathcal{W}(r^2)}}{r^2}\Delta^{-1}(r^2) + \left[\frac{d\Delta^{-1}(r^2)}{dr^2}\right]\right\},$$

displacement

partial derivative of the ghost-gluon kernel

- No lattice results for $\mathcal{W}(r^2)$
- Computed from its own SDE using lattice inputs





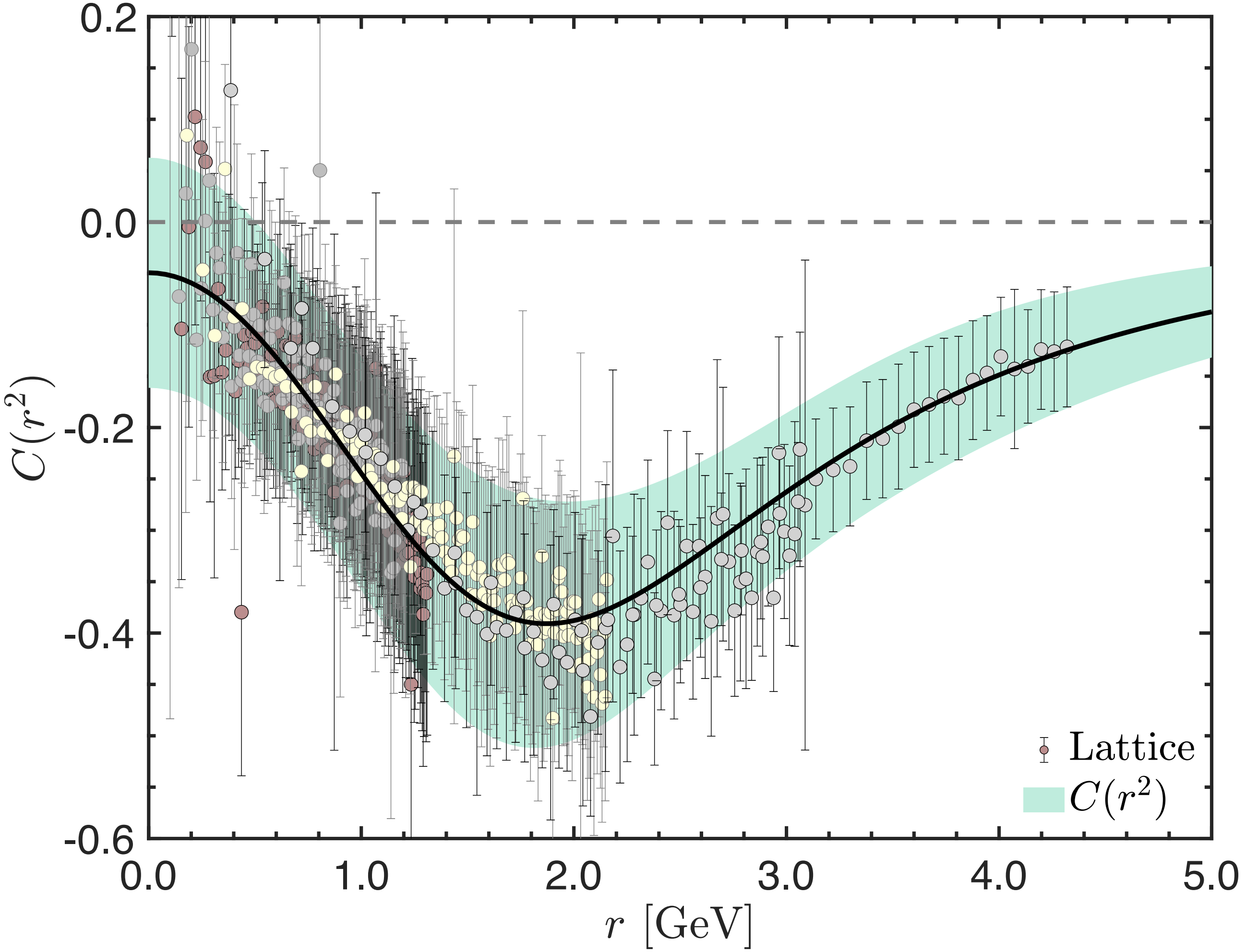
The result is dominated by a particular projection of the three-gluon vertex , evaluated on the lattice

$$\overline{\mathbb{\Gamma}}_{\alpha\mu\nu}(q,r,p) = P_{\alpha'\alpha}(q)P_{\mu'\mu}(r)P_{\nu'\nu}(p)L_{sg}(s^2) \times\left[(q-r)^{\nu'}g^{\mu'\alpha'} + (r-p)^{\alpha'}g^{\mu'\nu'} + (p-q)^{\mu'}g^{\nu'\alpha'}\right]$$

F. Pinto-Gómez, F. De Soto, M. N. Ferreira, J. Papavassiliou and J. Rodríguez-Quintero, *Phys.Lett.B* 838 (2023) 137737

Model-independent determination of the displacement function

- The lattice is "blind" to specific dynamical mechanisms



A.C.A., F.De Soto, M. N. Ferreira, J. Papavassiliou, F. Pinto-Gómez, C.D. Roberts and J. Rodríguez-Quintero, *Phys. Lett.B* 841 137906 (2023)

Conclusions

- The apparent simplicity of the QCD Lagrangian conceals an enormous wealth of dynamical patterns, giving rise to a vast array of complex ***emergent phenomena.***

- Gluon self-interactions generate a ***dynamical mass scale*** in the gauge sector of QCD.

- Dynamics and symmetry are tightly intertwined:

Displacement of the Ward identity ⟷ *BSE amplitude for pole formation*

- ***Smoking gun signal*** corroborates the action of the ***Schwinger mechanism*** in QCD and the ***emergence of a dynamical gluon mass***.